

National Aeronautics and  
Space Administration

**Lyndon B. Johnson Space Center**



# Applied Aeroscience and CFD Branch Overview

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# Lyndon B. Johnson Space Center

## Principal Mission: Human Spaceflight



# The Future of Human Space Exploration

## *NASA's Building Blocks to Mars*

U.S. companies  
provide  
affordable  
access to low  
Earth orbit

Learning the  
fundamentals  
aboard the  
International  
Space Station

Expanding capabilities  
by visiting an asteroid  
in a Lunar distant  
retrograde orbit

Traveling beyond low Earth  
orbit with the Space Launch  
System rocket and Orion crew  
capsule

Exploring Mars  
and other deep  
space  
destinations

*Missions: 6 to 12 months  
Return: hours*

*Missions: 1 month up to 12 months  
Return: days*

*Missions: 2 to 3 years  
Return: months*

Earth Reliant

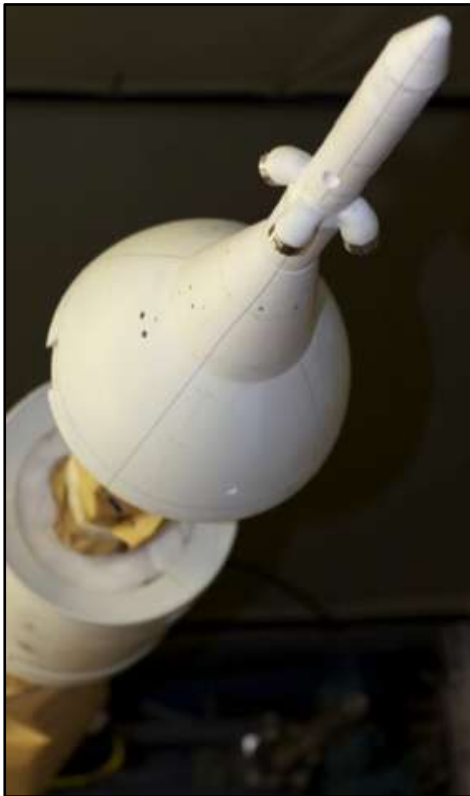
Proving Ground

Earth Independent

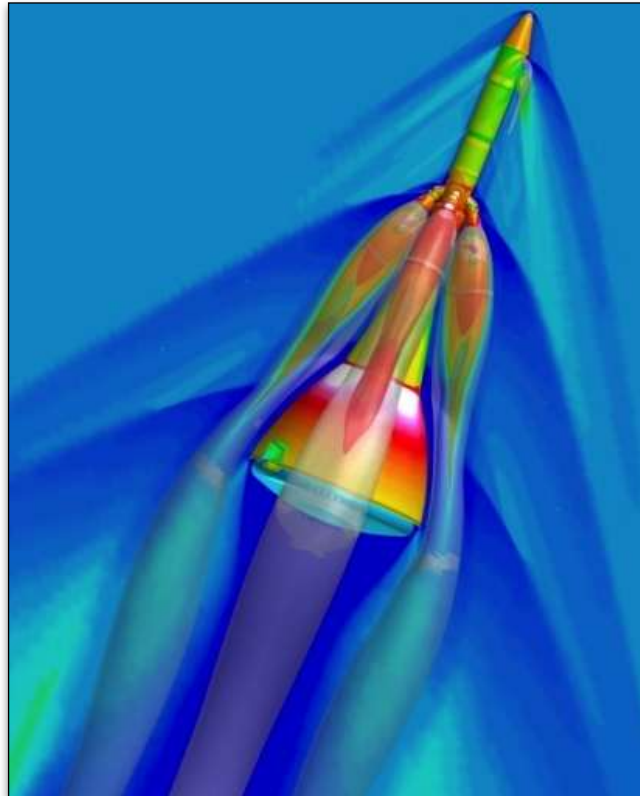
# Aeroscience Technical Competencies



- (1) Aerodynamic Characterization
- (2) Aerothermodynamic Heating
- (3) Rarefied Gas Dynamics
- (4) Decelerator (Parachute) Systems



Ground Testing

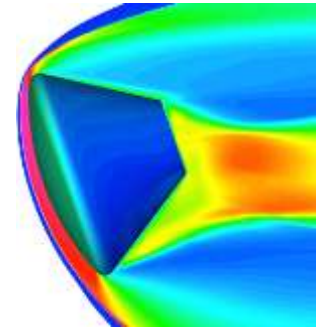


Modeling and Simulation



Flight Testing

# Principal JSC Initiatives & Aeroscience Support



## 1. Operate the International Space Station

- Aerodynamic & aerothermodynamic response for rarefied flows
- Plume modeling for visiting vehicles
- ISS end-of-life disposal

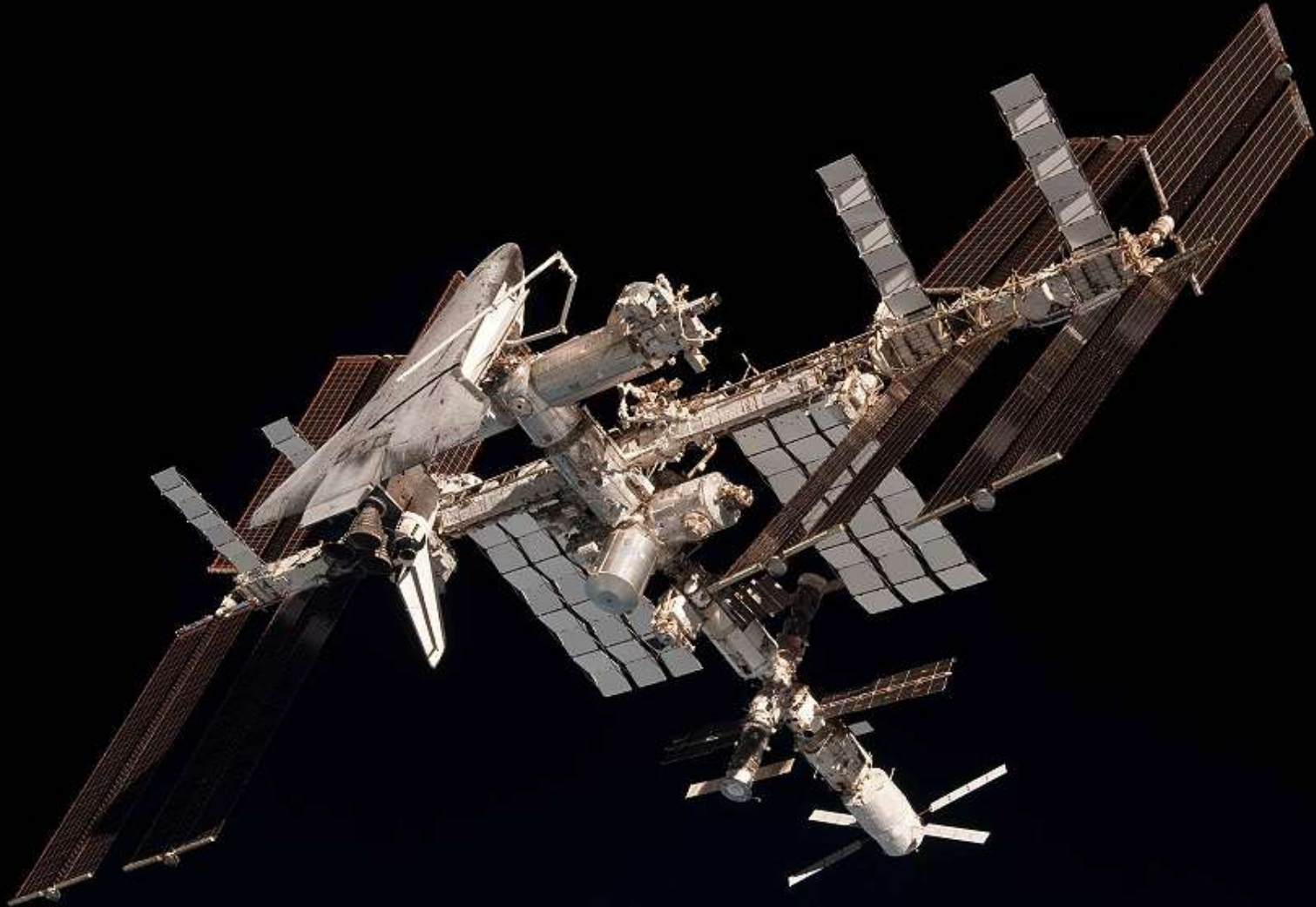
## 2. Develop the Multipurpose Crew Vehicle *Orion*

- Develop aerodynamic & aeroheating databases
- Support development of the parachute recovery system

## 3. Enable Commercial Access to Space

- Develop system requirements and assess design compliance
- Perform IV&V of partner aerosciences products
- Support reimbursable activities to commercial partners

# International Space Station Operations



# Commercial Crew Program

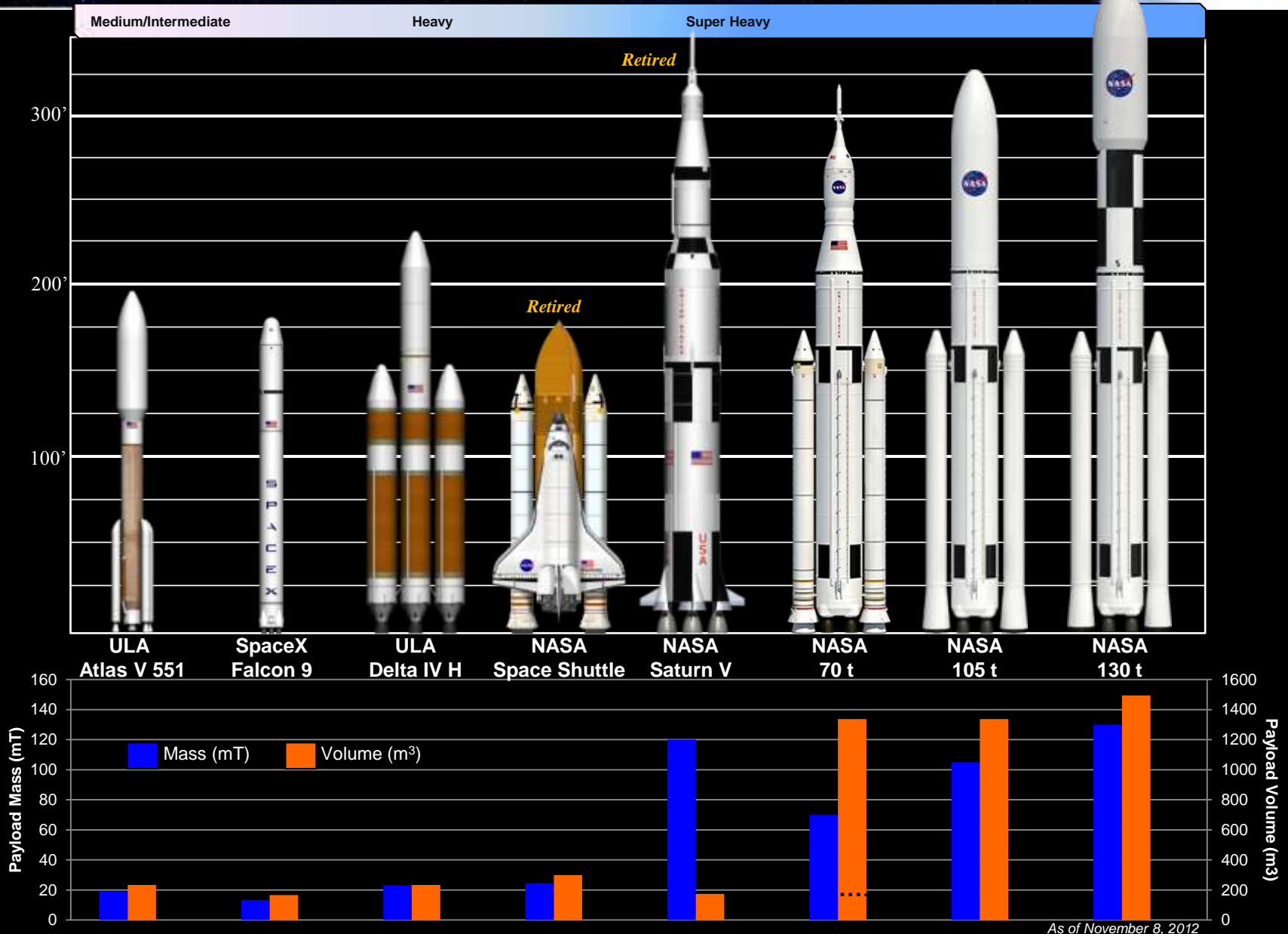


# NASA's Exploration Architecture

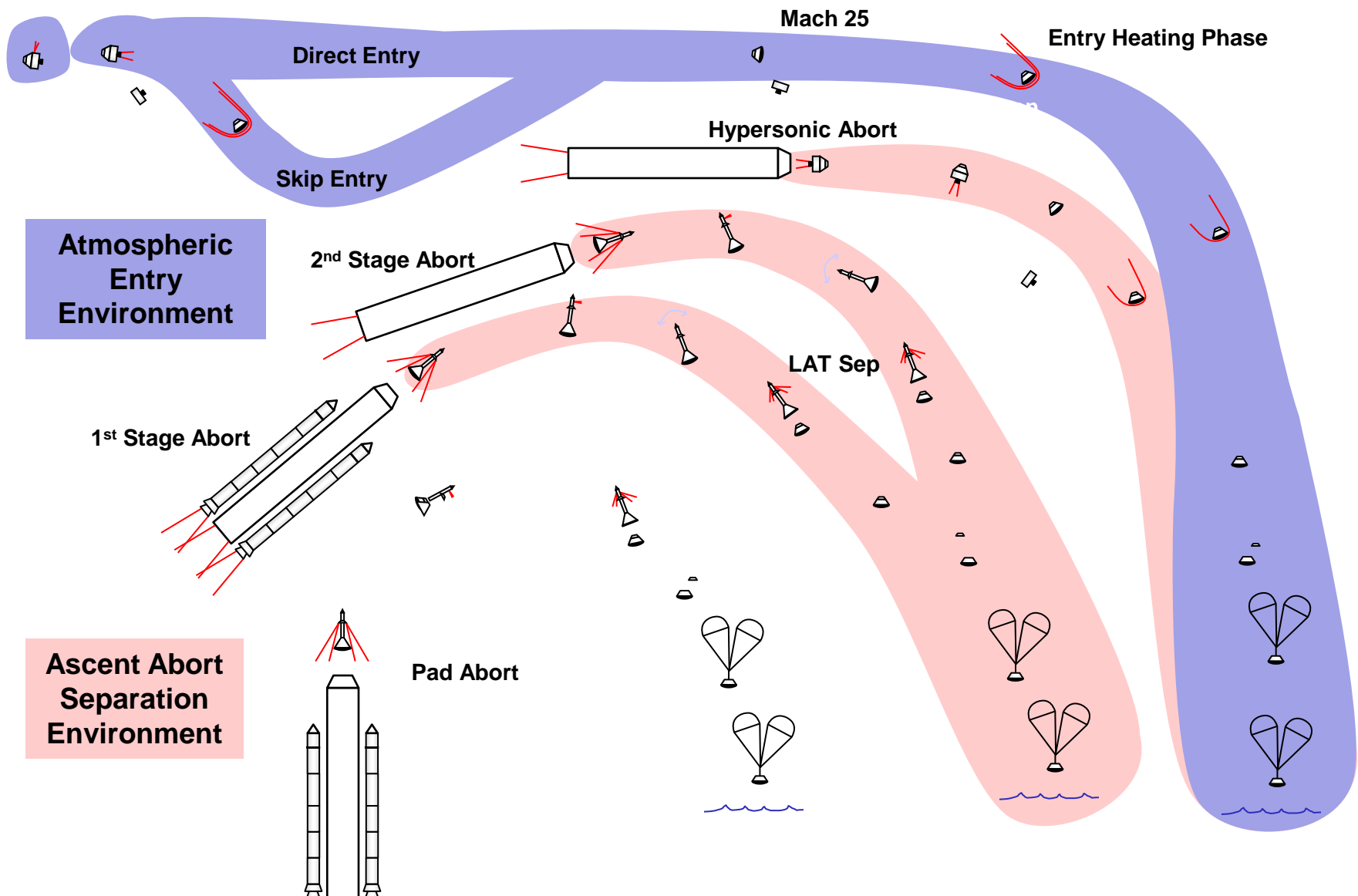
ORION | SPACE LAUNCH SYSTEM



# Capability Comparison



# Orion Aerosciences JSC Responsible Flight Regimes

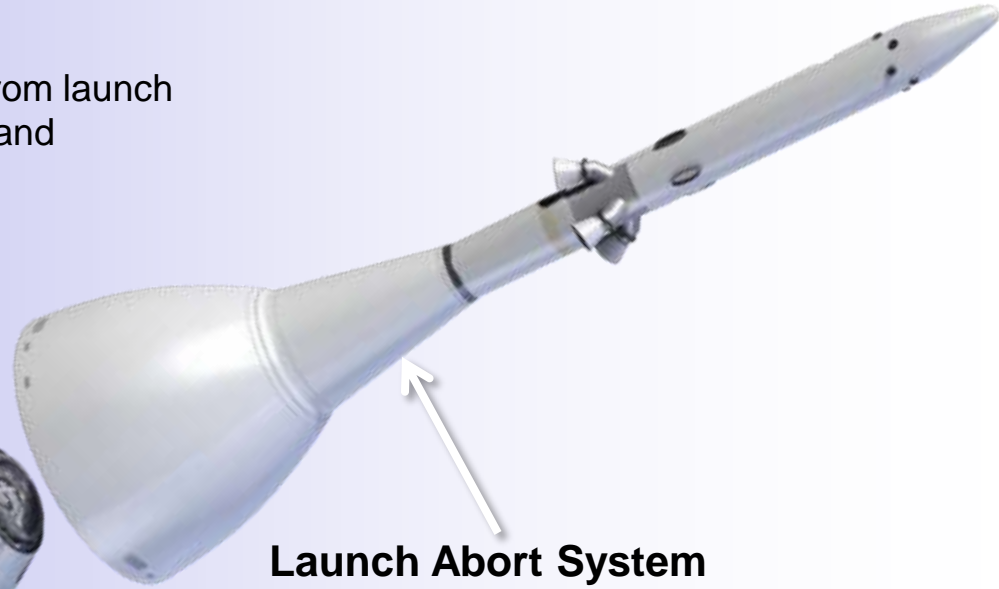


# The Orion Spacecraft



## Crew Module

Human habitat from launch through landing and recovery.

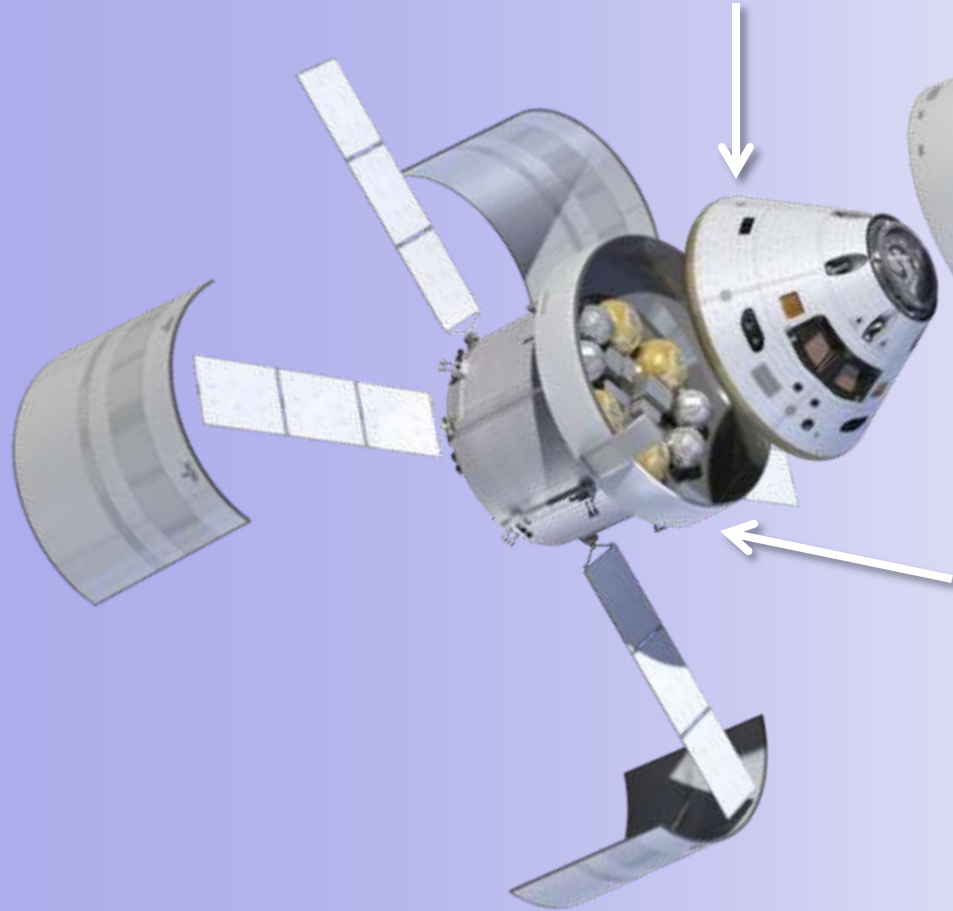


## Launch Abort System

Provides crew escape during launch pad and ascent emergencies.

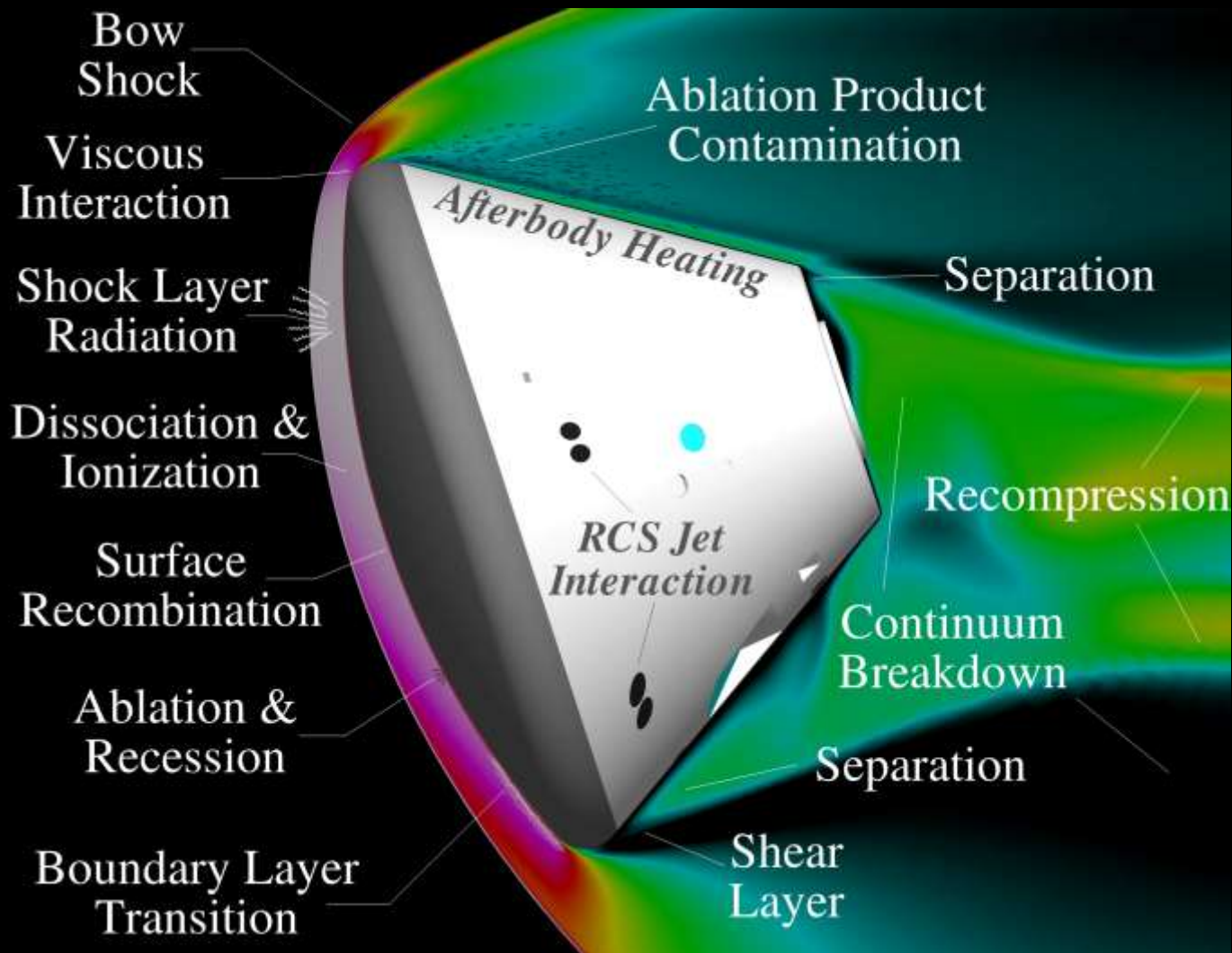
## Service Module

Power, propulsion and environmental control support to the Crew Module. Provided by the European Space Agency.





# Entry Aerothermodynamic Modeling



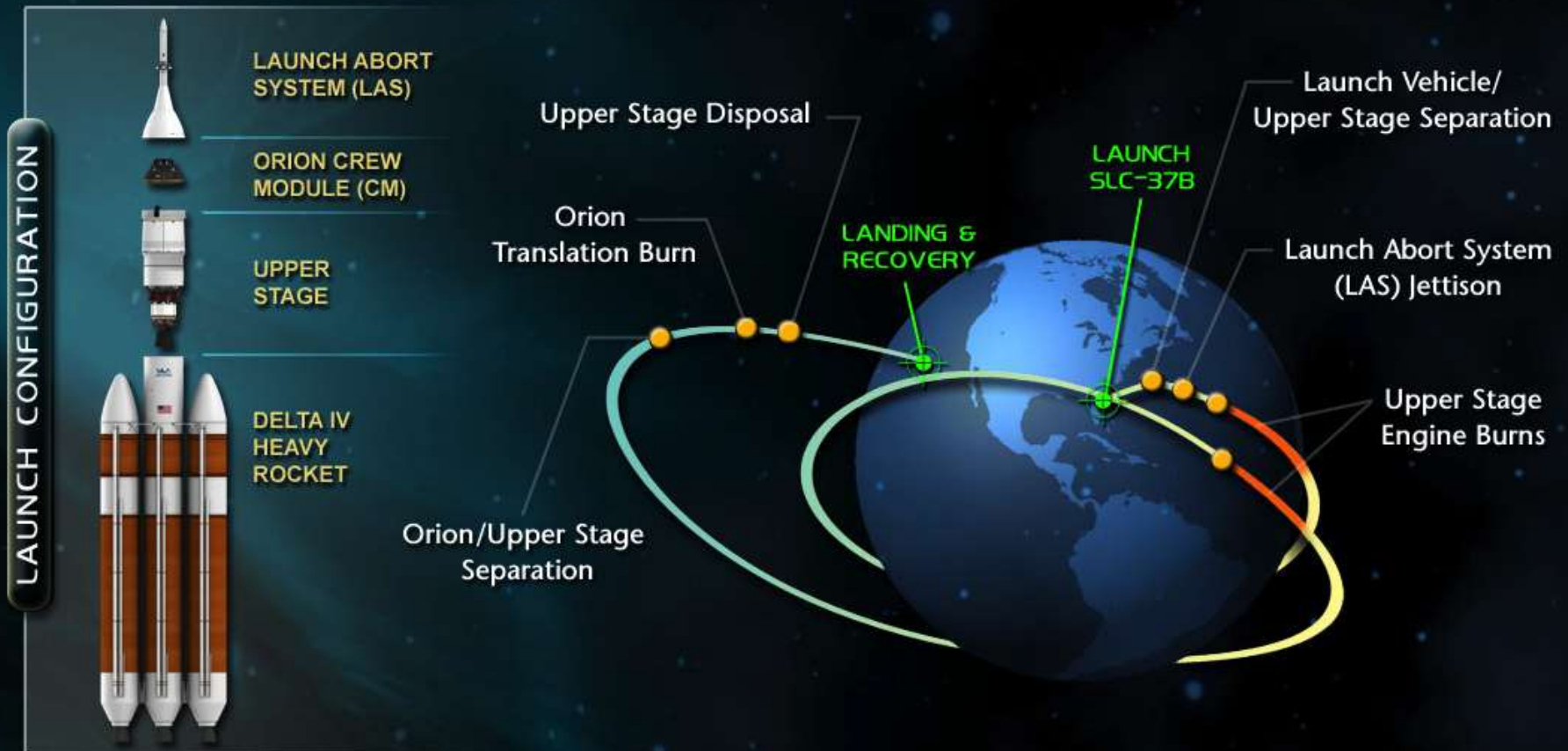
# Orion Exploration Flight Test 1 Upcoming December 2014



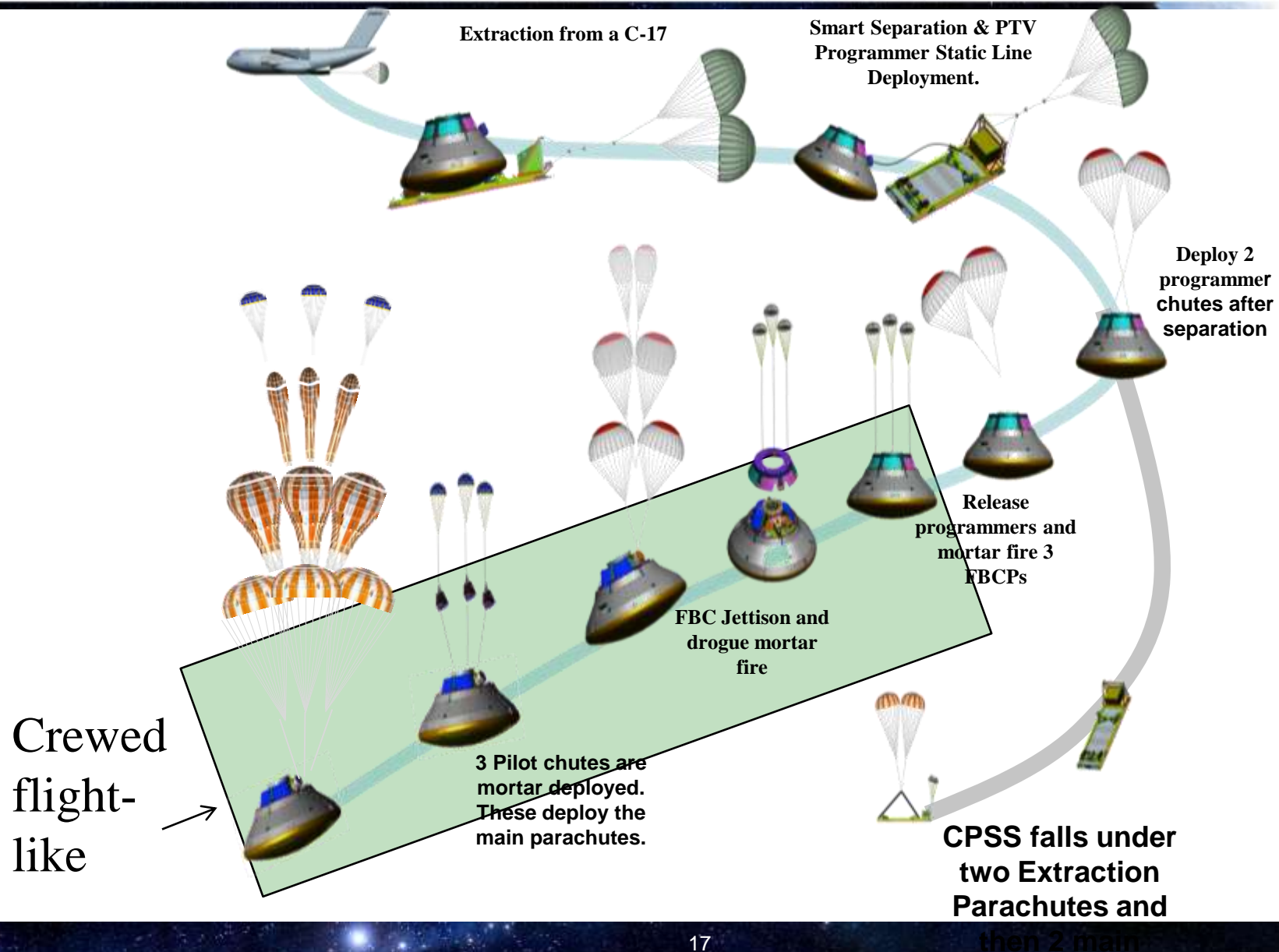
## EXPLORATION FLIGHT TEST ONE

### OVERVIEW

TWO ORBITS • 20,000 MPH ENTRY • 3,671 MILE APOGEE • 28.6 DEGREE INCLINATION



# Parachute Recovery System Development





# Technical Competencies

Aerodynamics

Aerothermodynamics

Rarefied Gas Dynamics

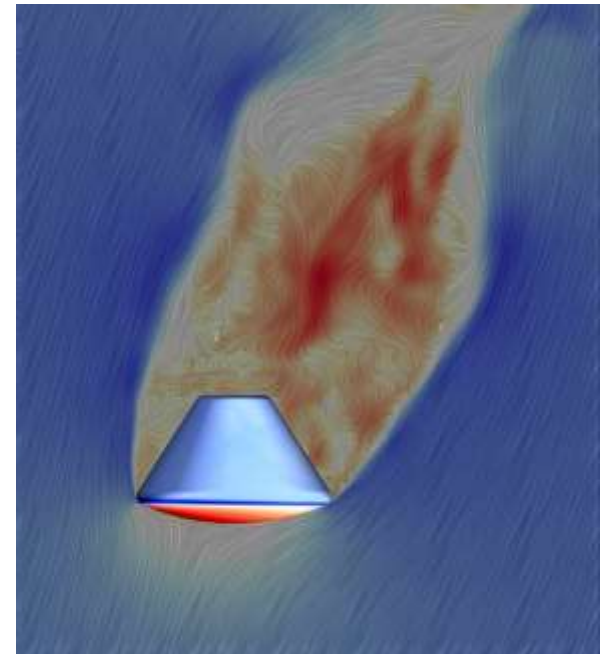
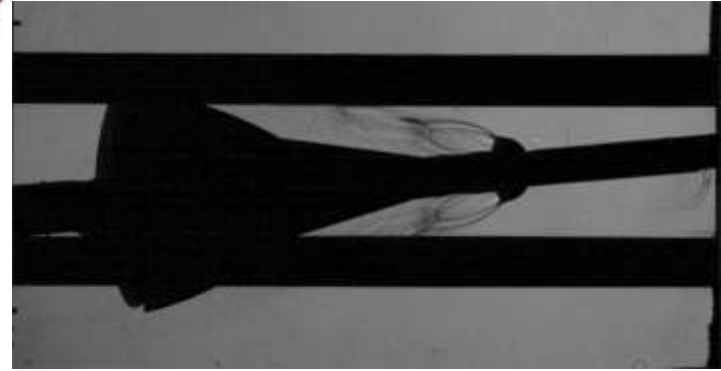
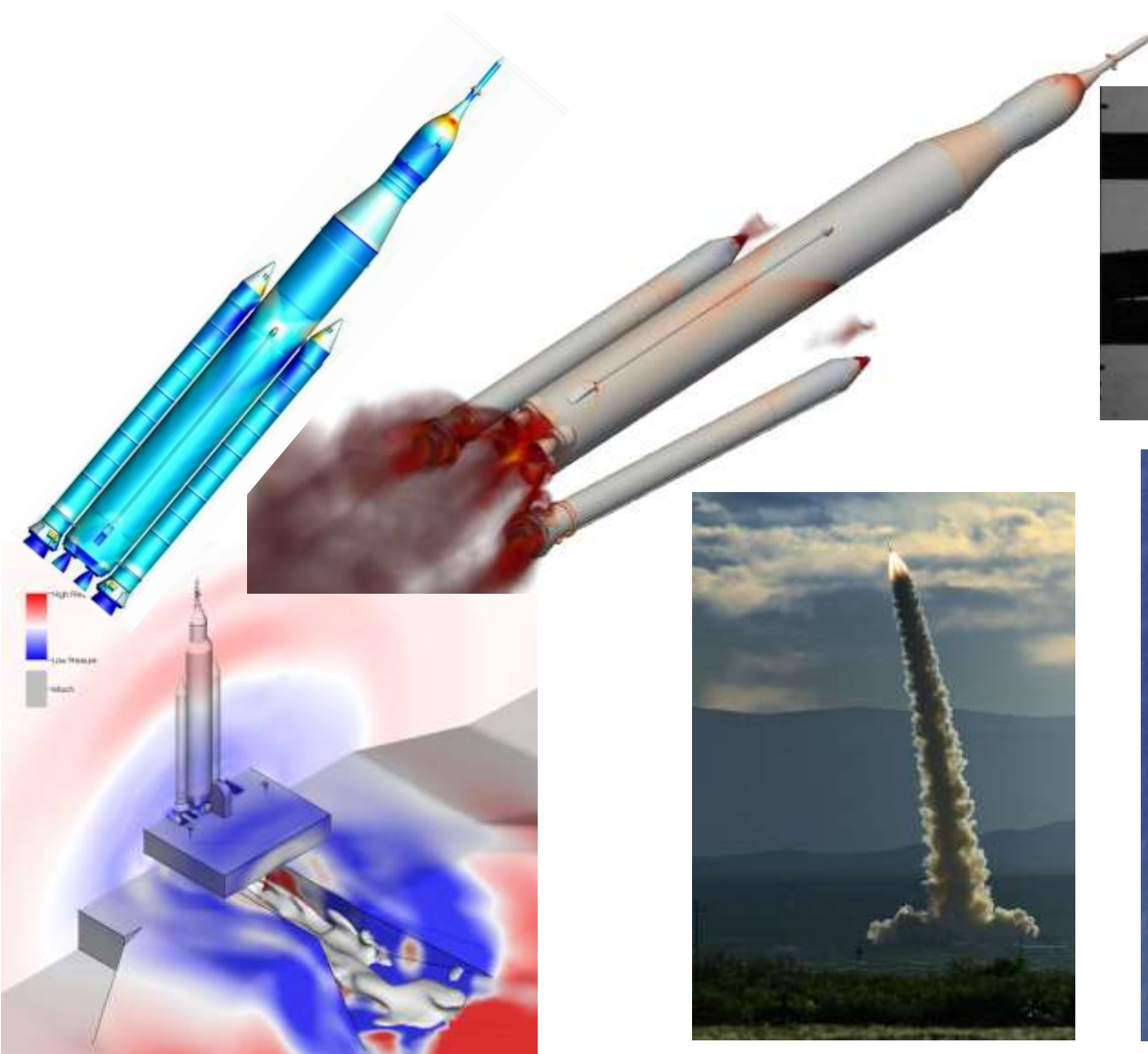
Decelerator Systems

# Aerodynamics Discipline Overview



- Provide comprehensive aerodynamic induced environments from ascent through entry and landing to **Trajectory** and **Structural analysts**.
- Products include
  - Ascent, entry and **abort** aerodynamics, external pressure distributions, protuberance air loads, **stability derivatives**, **acoustics/overpressure**, venting, **plume effects**, prelaunch wind effects and **wake environments** for parachute analysis.
- Tools
  - Computational Fluid Dynamics codes
  - Wind tunnels from subsonic through hypersonic regimes.
  - Flight tests

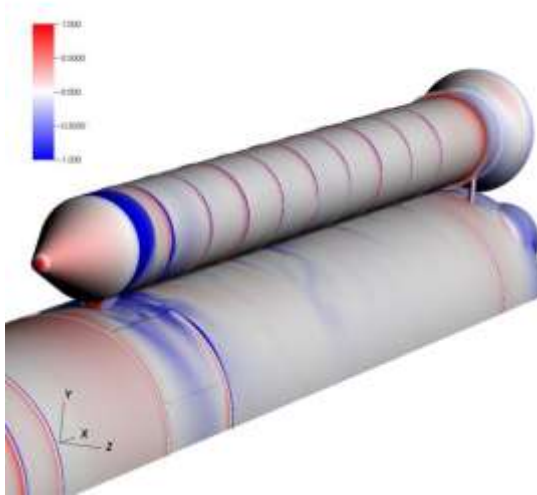
# Aerodynamics Discipline Overview



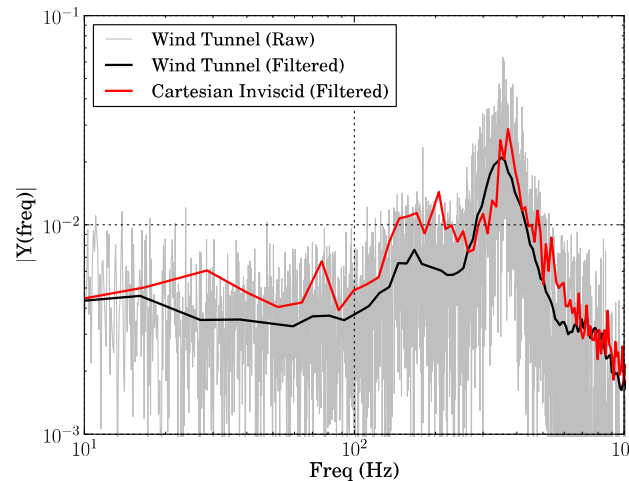
# Aerodynamics Challenge: Launch Acoustics



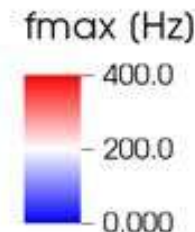
- Accurate, efficient prediction of unsteady transonic environments  
CFD requires small time steps to accurately capture physics.  
Wind tunnel testing requires  $\approx 5$  seconds of physical time to achieve statistical convergence.



(a)



(b)



AIAA 2011-3504

# Aerodynamics Challenge: Dynamic Stability



- Prediction of dynamic stability characteristics using CFD on a bluff body with jets in cross flow.



AIAA 2011-3504

# Aerothermodynamics Discipline Overview

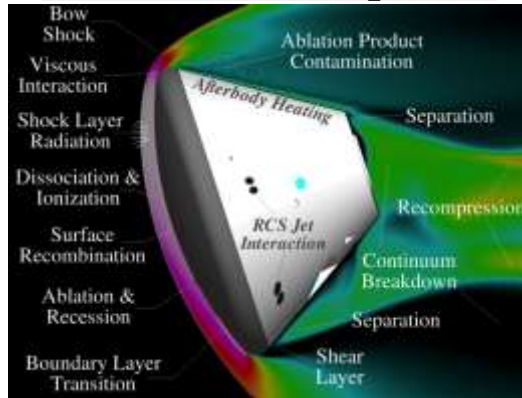


- Goal is to provide **heating environments to all external spacecraft components for all flight regimes**
  - Components: acreage, steps/gaps, seals, penetrations, protuberances, reaction control systems
  - Flight regimes: ascent, exo-atmospheric, entry
- Current customers include Orion, Commercial Crew, and technology development projects
  - Orion: Leads agency wide team that develops aerothermodynamic environment database, provides technical authority oversight, provides mission support (historically provided mission support and damage assessment for Orbiter)
  - Commercial Crew: Supports all commercial partners with both inline product development and technical authority oversight
  - Technology development: Leads development of high fidelity computational fluid dynamics (CFD) and ablator and thermal analysis (ATA) tools
  - Discipline level customers include thermal protection and guidance, navigation, and control communities: trajectory-based heating indicators, arcjet characterization and flight traceability assessment, coupled aerothermal-TPS simulations
- Product development utilizes multi-faceted approach including ground and flight testing, computational methods, historical data, and engineering-level analysis
  - Ground testing: Experience testing in every high quality aerothermal facility in nation. Orion work has included ~30 ground tests in over 10 facilities
  - Flight testing: Orion PA-1 and EFT-1, Orbiter flight tests for boundary layer transition, catalysis, and protuberance heating
  - Computational methods: CFD is the workhorse for acreage heating database development (DPLR, Loci-CHEM, OVERFLOW, US3D, FIN-S, DAC). ATA is primarily used for wind tunnel and flight environment reconstruction (CHAR). Boundary layer transition (STABL)
- Emphasis is placed on overcoming technical challenges to improve product quality
  - Environments on geometrically complex components: ascent vehicles, cavities and protuberances, steps/gaps
  - Jet interaction environments: launch abort systems, RCS
  - Boundary layer transition: physics based and empirical methods
  - Fluid-surface interactions: ablation, shape change, catalysis

# Aerothermodynamics Discipline Overview



## Database Development



*Technical Challenges:*

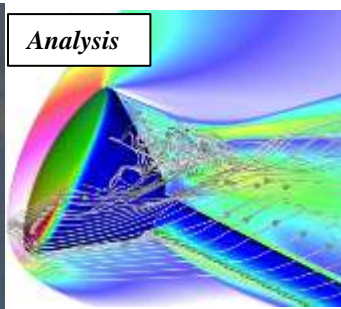
*Ground Testing*



*Flight Testing*

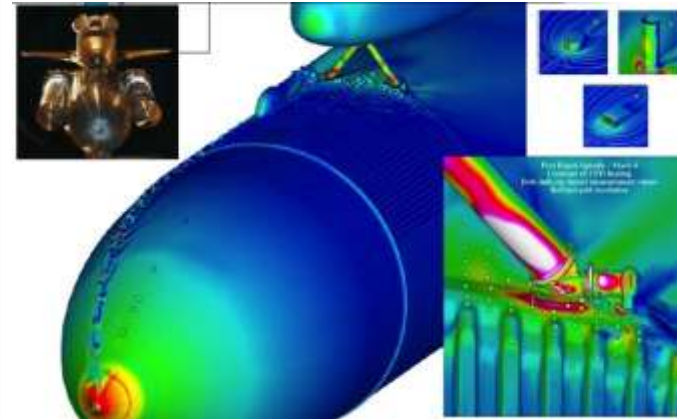
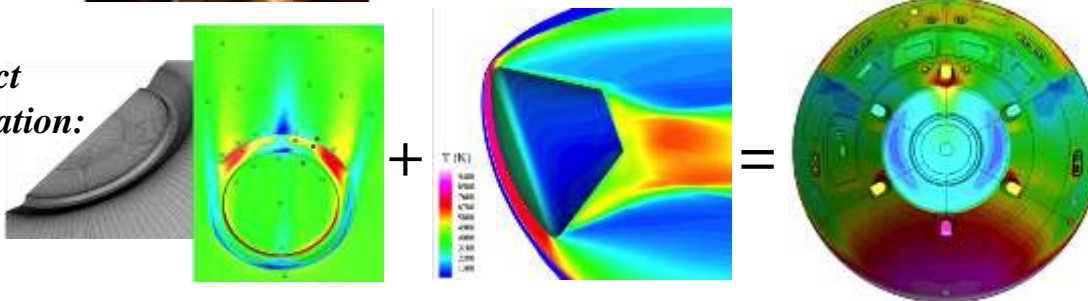


*Analysis*



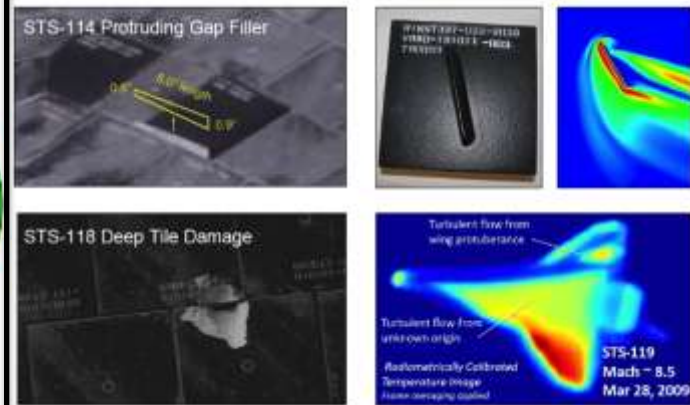
*Inputs:*

*Product Integration:*



*Ascent Environment Testing and CFD*

*Mission Support, Damage Assessment, and Flight Testing*



# Aerothermodynamics Challenge: Orion RCS Jet Interaction Heating

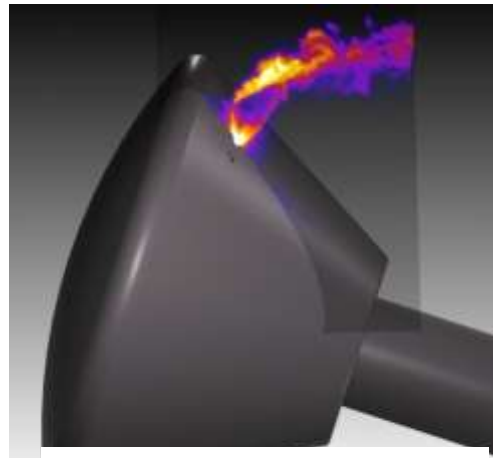


*Predicting heating induced from 12 RCS jets on Orion Crew Module is a primary technical challenge due to unsteady flow interactions over a broad range of freestream conditions*

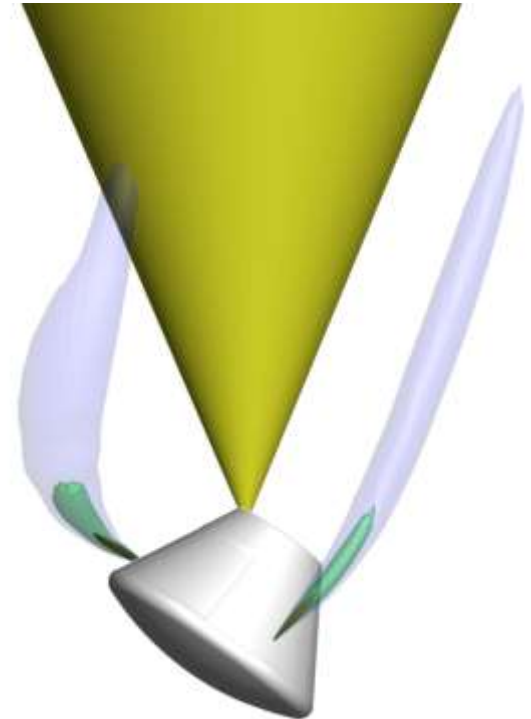


*CUBRC RCS model with 400+ gages*

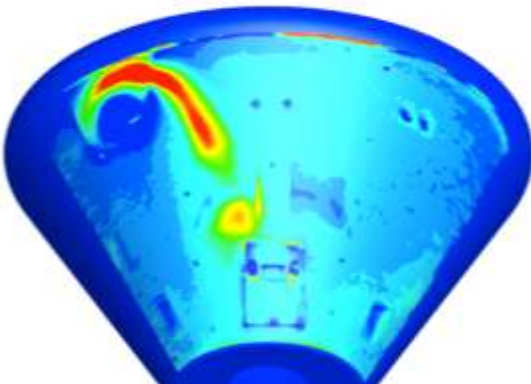
*Orion has conducted 6 tests to develop RCS environments*



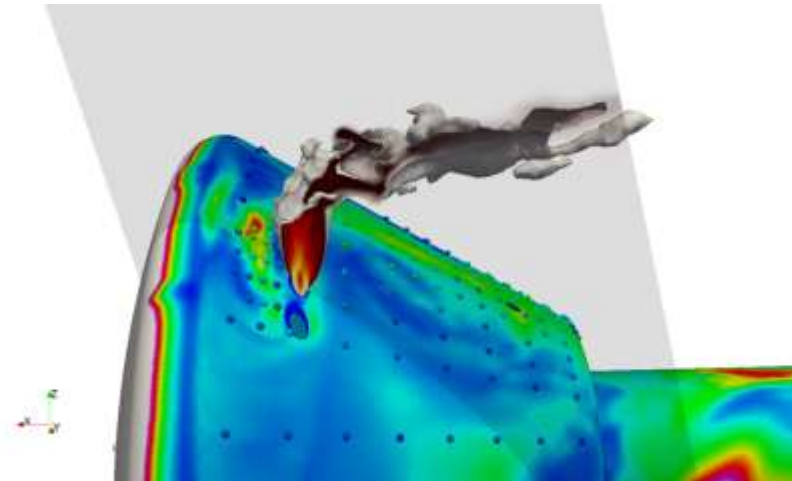
*PLIF flow visualization of roll jet*



*Investigation of RCS jet interaction with parachute riser lines*



*LaRC RCS model with TSP*



*Initially reliant on empirical models alone, Orion team has been developing a validated CFD capability*

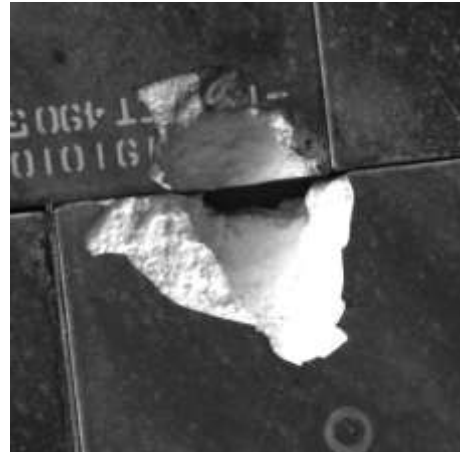
# Aerothermodynamics Challenge: STS-118 Deep Tile Damage



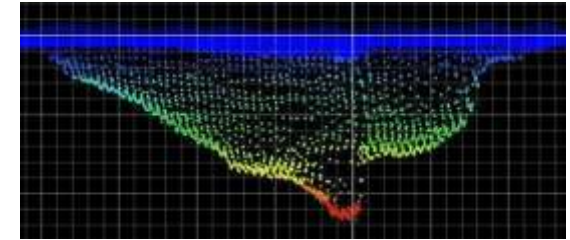
*Location of tile damage due to  
ET ice impact on ascent*



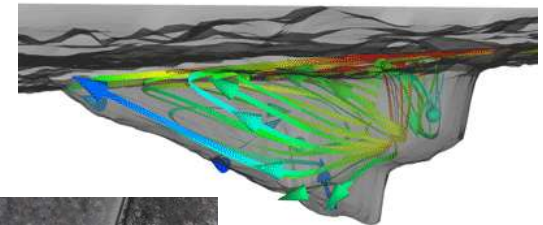
*Photograph during  
focused inspection*



*Laser Doppler Range Imaging used to get  
3D details of damage geometry*

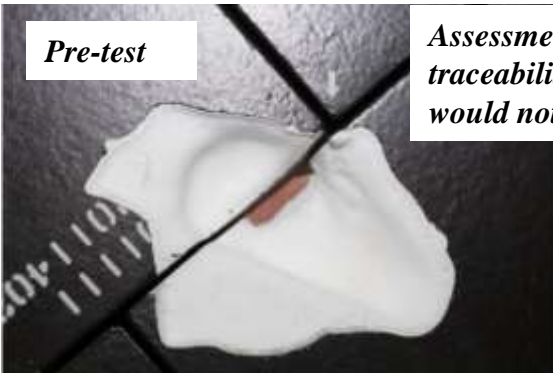


*In-mission CFD result*



*Pre-test*

*Assessment of ground-to-flight  
traceability effects indicated that damage  
would not propagate during re-entry*



*Post-test*



*Arcjet test showed the  
potential for damage  
propagation*



*Post-flight photograph showed no  
damage propagation.*

*EG3 supported DAT  
with arcjet test  
support, aerothermal  
assessment of re-  
entering with damage,  
and explored  
environments on  
potential repair  
options.*

# Flight Vehicle Boundary Layer Transition Prediction

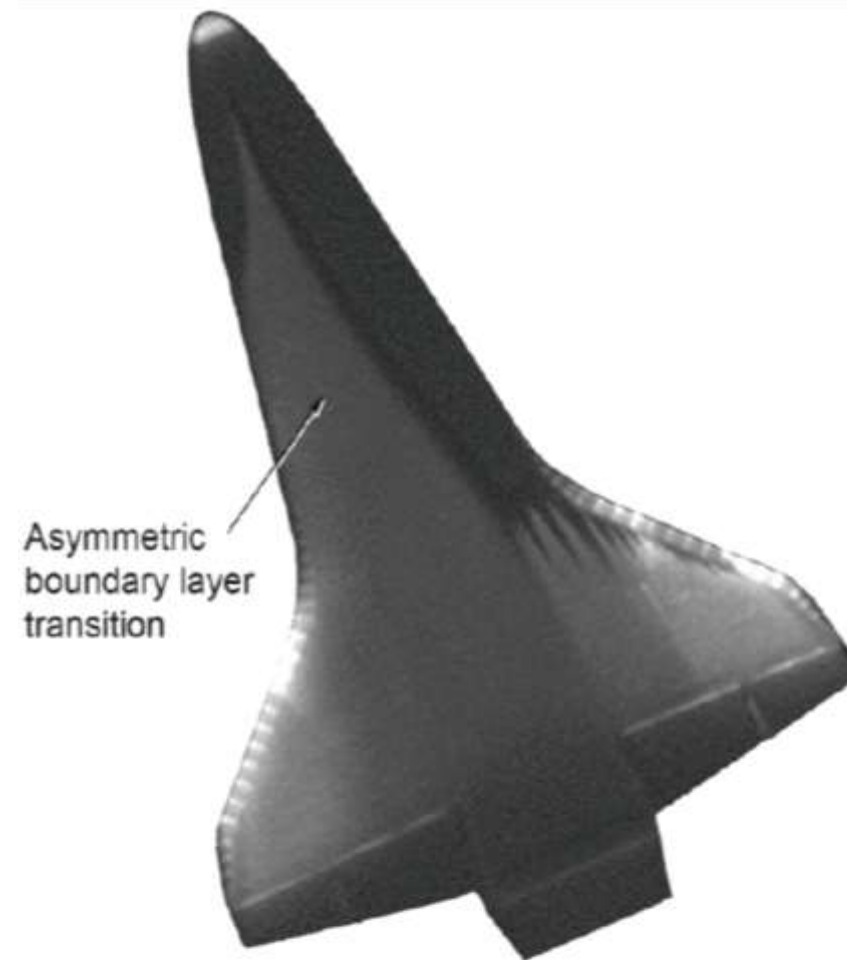


Figure 3: Thermal image of Endeavour during STS-134 re-entry near the point of closest approach, Mach 5.8, AOA = 28.8 deg, Slant Range ~32 nautical miles.

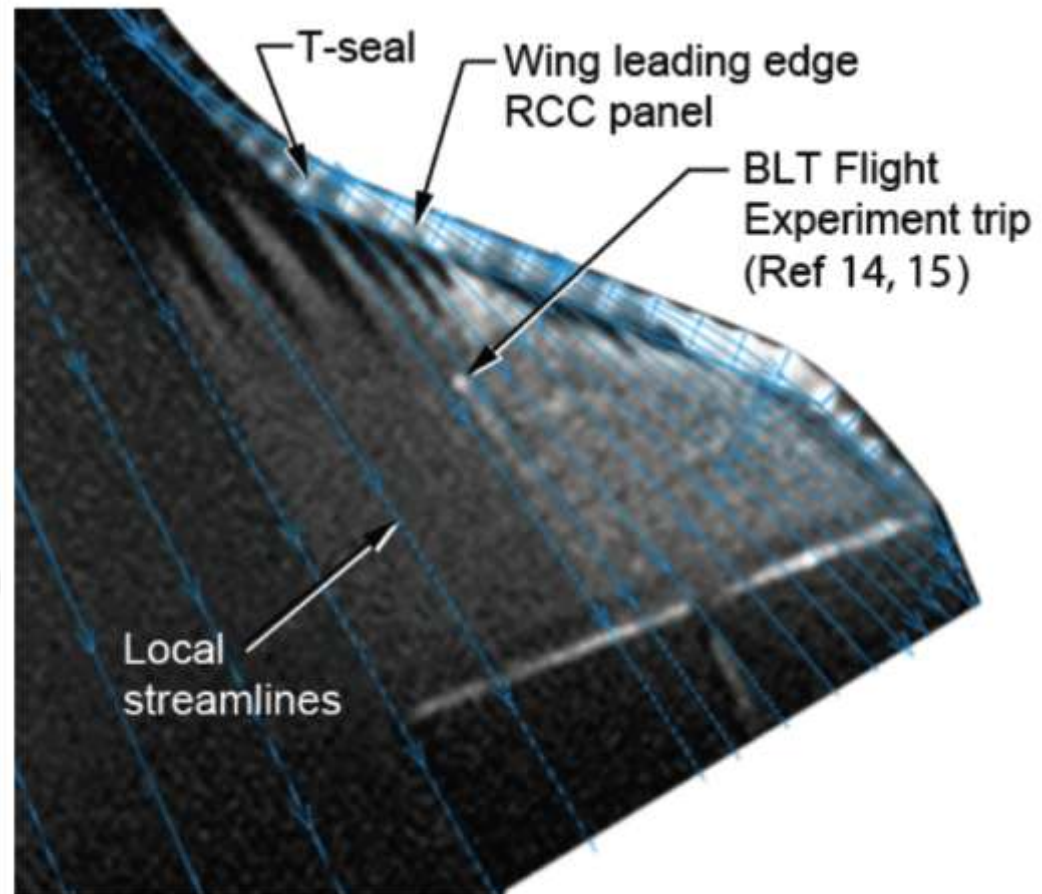
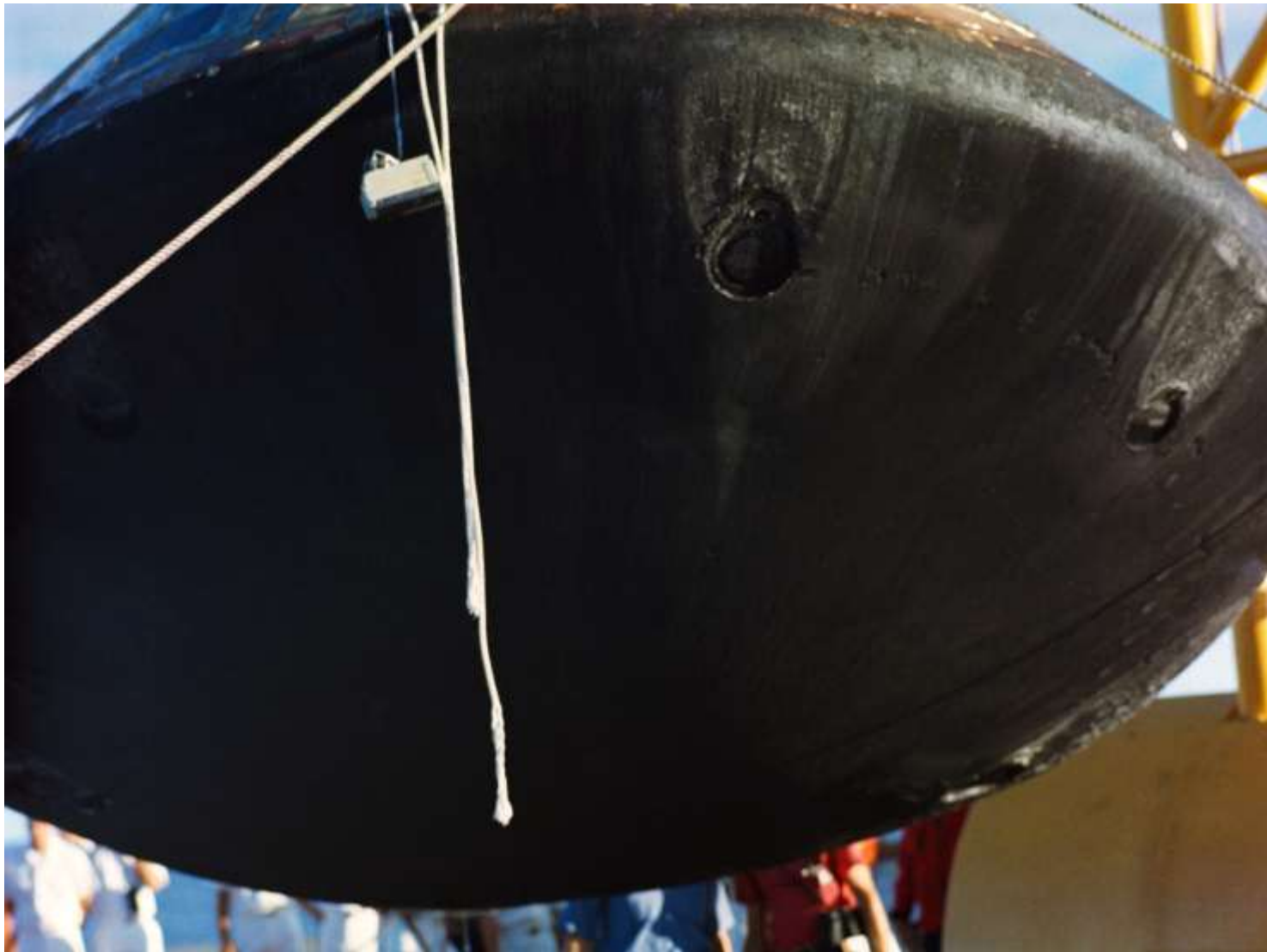


Figure 6: Transition patterns on Port wing. Turbulent wedges appear aligned with RCC panel T-seals. Mach = 5.8, AOA = 28.8 deg.

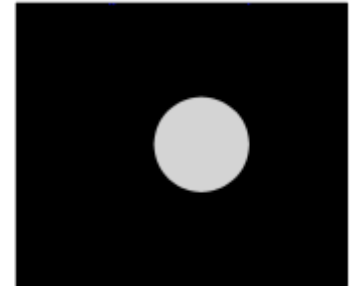
# Flight Vehicle Boundary Layer Transition Prediction



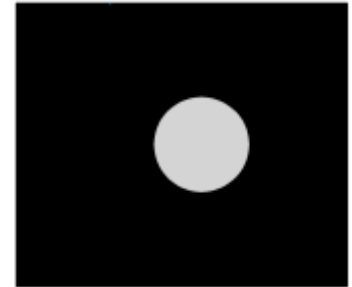
# Rarefied Gas Dynamics Discipline Overview



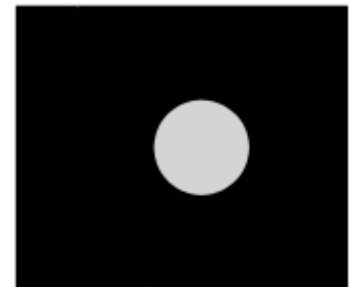
- Objective:
  - Provide state-of-the-art capabilities and tools for analysis of a variety of low density, non-continuum flows (from transitional to free molecular)
- Customers:
  - International Space Station
  - Orion
- Products:
  - **Thruster plume modeling** and plume impingement analyses
  - **Spacecraft aerodynamics and aeroheating** (reentry, aerocapture, aerobraking, orbital decay)
  - Application, development, maintenance of several computational tools (RPM3D and DAC (which is also distributed))
- Methods:
  - Mainly computational modeling
- Tools:
  - DAC (DSMC code)
  - RPM3D (Engineering tool for plume impingement analyses)
  - FREEMO (Free molecular code)
  - Other computational tools (RAMP, BLIMP, DPLR, ...)



Continuum



Transitional

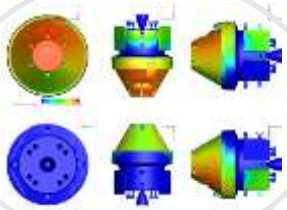


Free molecular

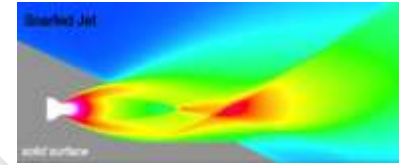
# Rarefied Gas Dynamics Discipline Overview



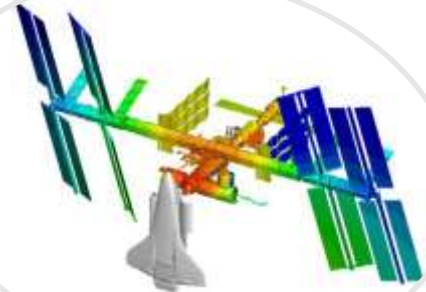
Aeroheating



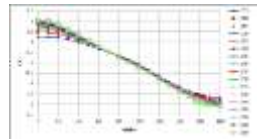
Plume modeling



Plume impingement



Aerodynamics



Free Molecular

Transitional

Continuum



# International Space Station Proximity Operations



ISS020E041290

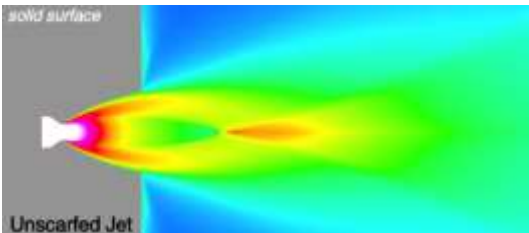


# Rarefied Gas Dynamics Challenge: Plume impingement effect analyses



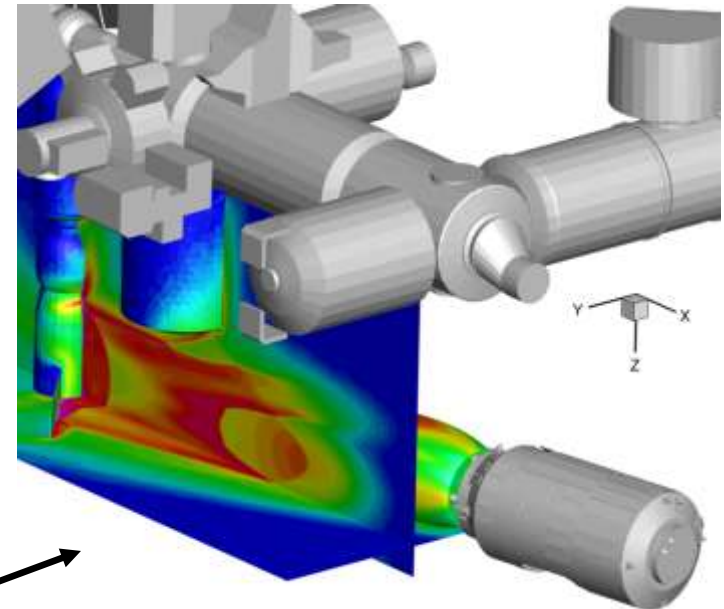
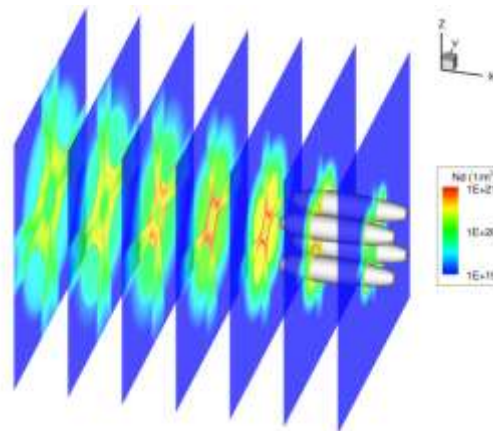
- HTV3 Main engine abort

- Flow expands from continuum in the nozzle to free molecular in the far field
- Complex flow fields must be properly modelled at each stage



Step 1:  
Near field modeling  
(Continuum -> CFD)

Step 2:  
Far field modeling  
(Transitional -> DSMC)



Step 3:  
Surface interaction modeling  
(Transitional -> DSMC or  
Free molecular -> Engineering tool)

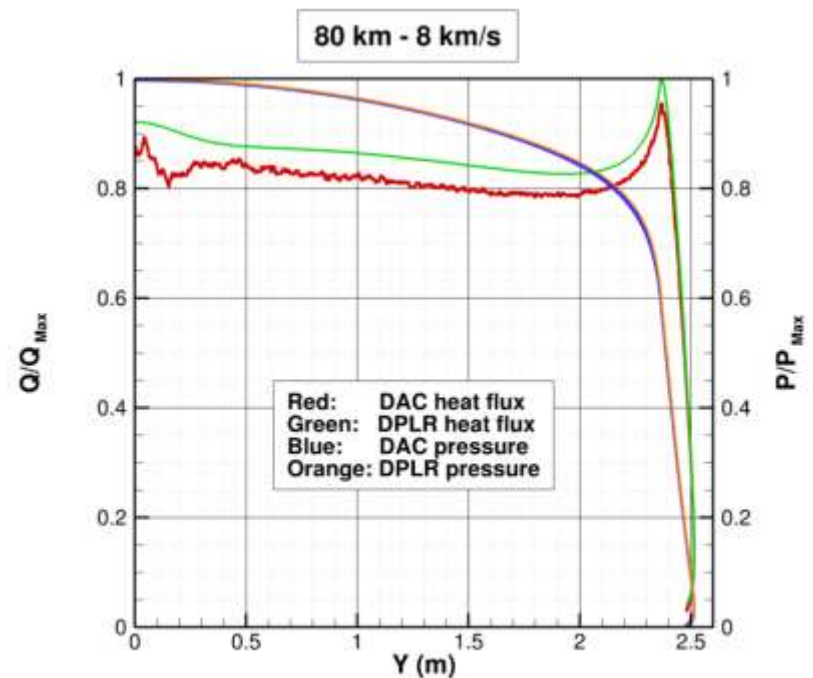
# Rarefied Gas Dynamics Challenge: Bridging the gap between CFD and DSMC



- The DSMC method can be used to model continuum flows but is generally too expensive to use for real-life problems
- For re-entry databases, a bridging function is used between the highest CFD solution and the lowest DSMC solution → not as accurate a model in that region as everywhere else

## Challenges:

- Match gas parameters and chemistry models between codes
- Improve the DSMC code efficiency
- Incorporate advanced models in the CFD code to better model the rarefaction effects



Surface properties on a capsule heat shield at 80 km and at zero angle of attack and sideslip angle with out-of-the-box codes

# Decelerator Systems Discipline Overview



- The **Decelerator Systems** Discipline has significant experience in guided and ballistic parachute system development
  - **Design, development, performance evaluation, and certification**
- The team currently provides expertise to several high-visibility NASA projects & programs:
  - Orion capsule development (Chief Engineer and hardware design support)
  - Commercial Crew (Design reviews and expert consultation)
- Methods and tools include:
  - Testing: Air drop testing, ground testing
  - Analysis: State-of-the art parachute system modeling published at technical conferences
  - Measurements: Innovative instrumentation and avionics
  - Partnerships with academia to develop Fluid Structure Interaction models of parachutes

# Decelerator Systems Team Overview



Parachute Test Vehicle



Sub-Scale Wind Tunnel Tests

Parachute Compartment Drop Test Vehicle

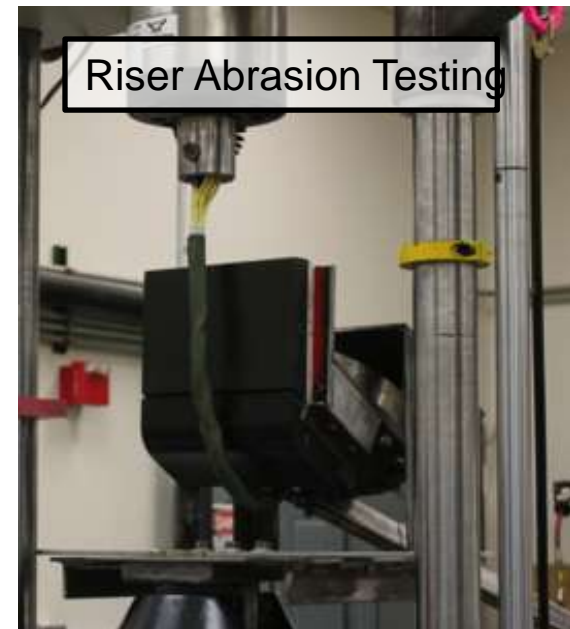


Parachute Deployment Testing



Air Drop Testing

Riser Abrasion Testing



# Wide Operation Space & Fault-Tolerance



- Parachute design is complicated due to a wide range of operating conditions
  1. Pad abort → get the parachutes out fast
  2. Nominal reentry → staged deployment to manage loads
  3. Final design is a compromise, which is the essence of engineering
- Fault tolerance is also a design requirement



# Decelerator Systems Challenge: Pendulum Motion Under Two Main Parachutes



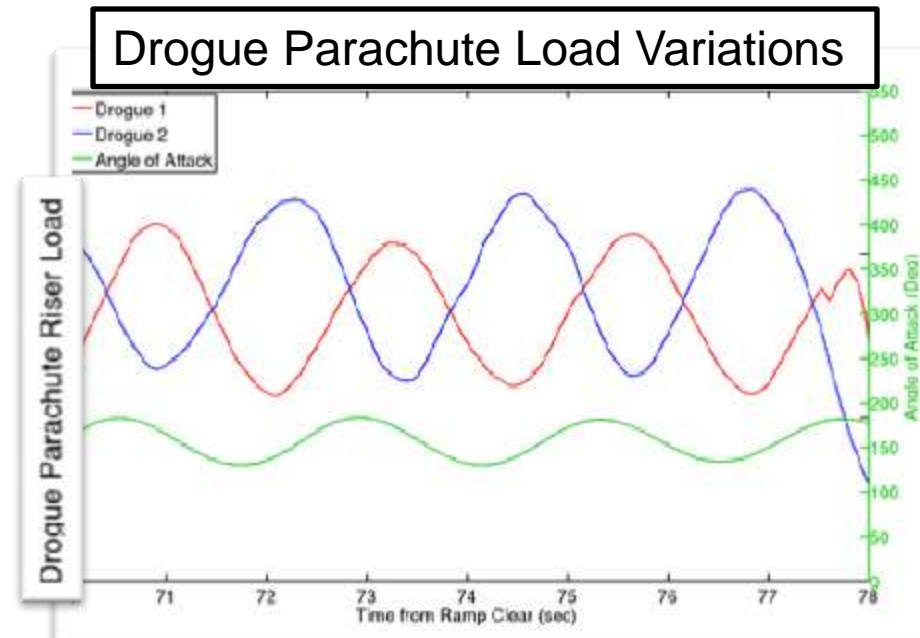
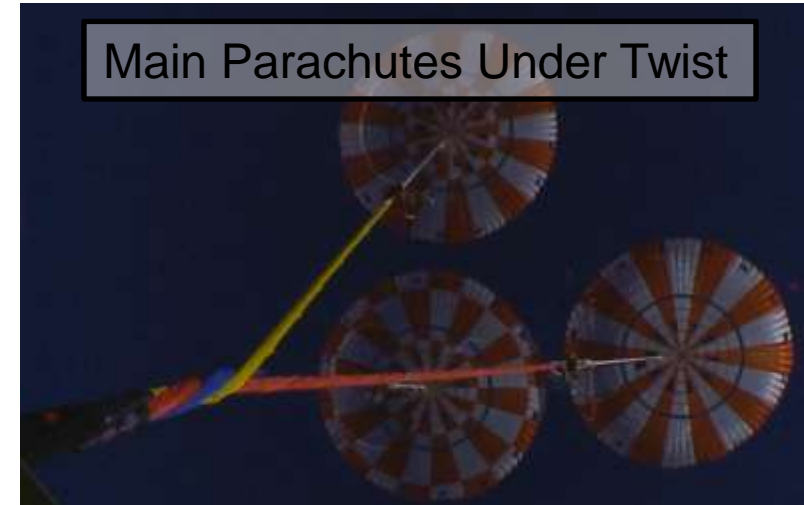
- Orion parachute development testing has included 4 tests with 2 main parachutes (nominally 3) to understand rate of descent characteristics with a failed main parachute
- During 2 of the 4 tests, the parachute & test vehicle system experienced an unexplained pendulum motion
  - Could effect touchdown incidence angle
- The main parachutes have a high drag coefficient and tend to “glide”
  - Both parachutes have glided together instead of exhibiting the somewhat random motion observed in most parachute cluster testing
- This phenomenon has not been reported previously and is currently under investigation
  - Complex interaction between the aerodynamics, system mass properties, and contact modeling
- Tools and methods being used to understand the complex phenomenon include:
  - Detailed trajectory reconstructions
  - Fluid Structure Interaction (FSI) modeling
  - Parachute aerodynamic sensitivity studies



# Parachute Load Amplification Due to Riser Twist & Capsule Dynamics



- The Orion parachute team has observed large (~50%) variations in riser loads during drop testing when the risers twist up
  - This phenomenon has not previously been one of the design considerations for cluster parachute systems
  - Twist is induced by vehicle motion below the parachutes & random parachute motions
- The changes in load are in phase with vehicle dynamics once the risers are twisted
- Monte Carlo trajectory simulations are being used to understand the likelihood of this phenomenon taking place when the parachutes are highly loaded
- A detailed ground test program is underway to understand the potential magnitude of the variations





# Tools & Capabilities

# Tools & Capabilities



## Computational Tools

		Aerodynamics	Aerothermal
ARC	Cart3D	X	
ARC	ChimeraGridTools	X	X
ARC	CBAero	X	X
ARC	DPLR	X	X
ARC	NEQAIR		X
ARC	Pegasus	X	X
JSC	CHAR		X
JSC	DAC	X	X
JSC	Debris	X	
JSC	OrionAeroAPI	X	
JSC	RPM3D	X	X
JSC	SNEWT	X	
LaRC	OVERFLOW	X	X
MSFC	ARTIF		X
MSFC	Loci-CHEM	X	X
University of Minnesota	STABL	X	X
Sandia National Labs	DAKOTA		X

## Test Facilities

		Aerodynamics	Aerothermal
ARC	9-Foot Supersonic Wind Tunnel	X	
ARC	11-Foot Transonic Unitary Plan Facility	X	
ARC	Electric Arc Shock Tube		X
ARC	Flight Mechanics Lab Test Cell 2	X	
ARC	Hypervelocity Free-Flight Ballistic Range	X	X
ARC	National Full-Scale Aerodynamics Complex	X	
LaRC	4-Foot Supersonic Unitary Plan Wind Tunnel	X	
LaRC	20-Foot Vertical Spin Tunnel	X	
LaRC	Aerothermodynamics Laboratory 31-Inch Mach 10 Air Facility	X	X
LaRC	Aerothermodynamics Laboratory 20-Inch Mach 6 Air Facility	X	X
LaRC	National Transonic Facility	X	
LaRC	Transonic Dynamics Tunnel	X	
AEDC	16-Foot Transonic Wind Tunnel (16T)	X	
AEDC	Aerodynamic 8-Foot Transonic Wind Tunnel (4T)	X	
AEDC	Hypervelocity Wind Tunnel (HT9)	X	X
Boeing	Polysonic Wind Tunnel (PSWT)	X	
Caltec	T5 Hypervelocity Shock Tunnel Facility		X
CUBRC	Cornell Aeronautical Laboratory (CAL) 8-Inch Shock Tunnel	X	X
CUBRC	Large Energy National Shock Tunnel (LENS)	X	X
CUBRC	Large Energy National Shock Tunnel (LENS II)	X	X
CUBRC	Large Energy National Shock Tunnel (LENS XX)		X
Eglin AFB	ARFB Ballistic Range	X	
Lockheed Martin	High Speed Wind Tunnel	X	
Texas A&M	Oran 3W Nicks Low-Speed Wind Tunnel	X	
U.S. Navy Washington	Aeronautical Laboratory Kirsten Wind Tunnel	X	
U.S. Air Force Academy	Subsonic Wind Tunnel	X	

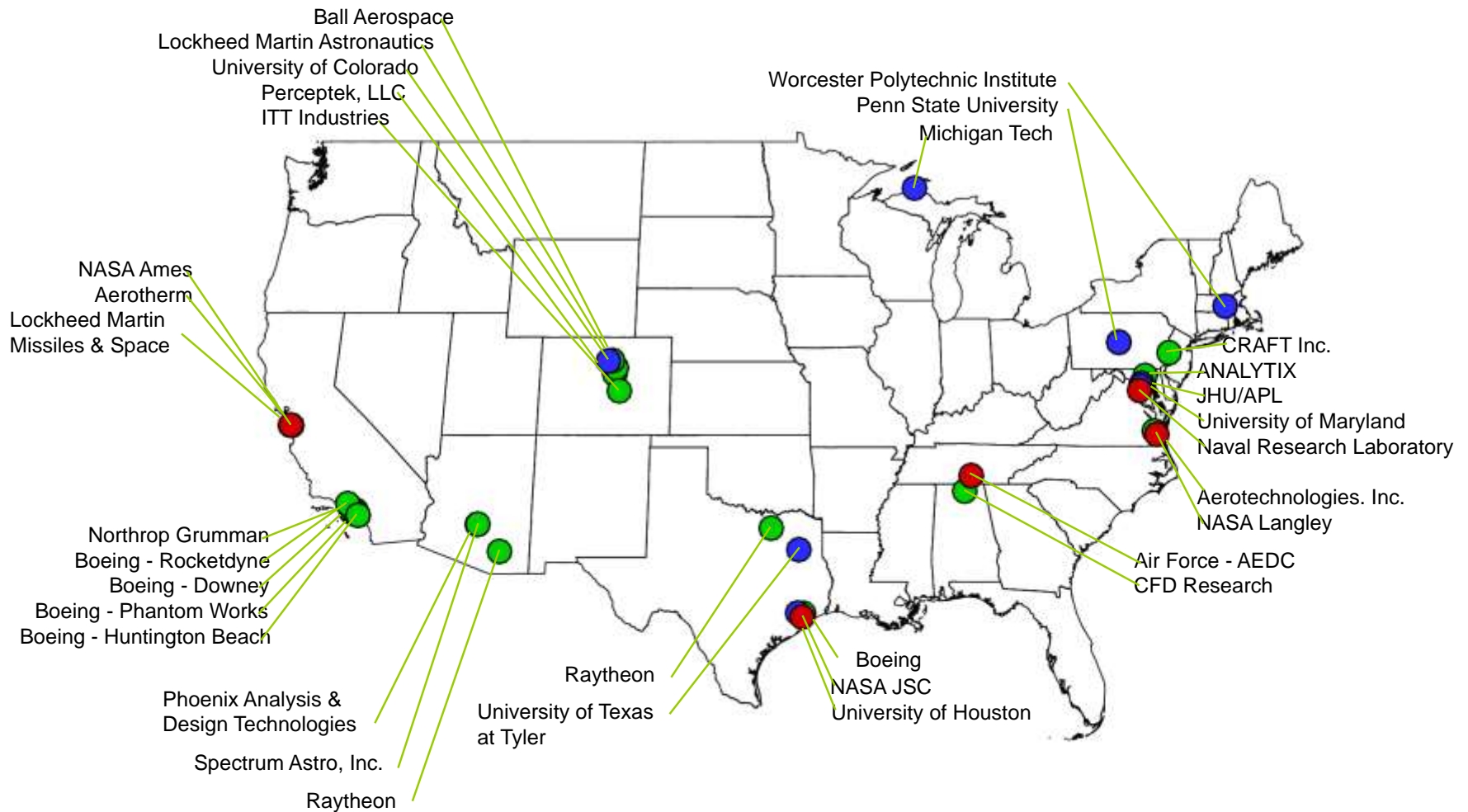
# DAC's User Base



● NASA or DoD

● Industry

● University



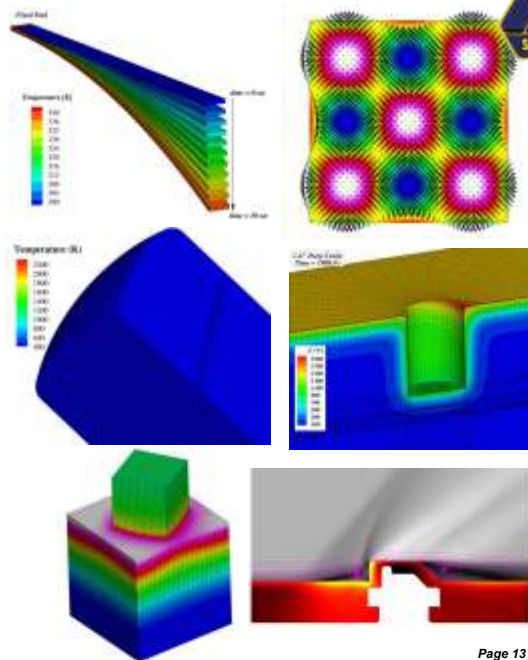
# CHAR - Capabilities & User Base



**JSC**  
**ARC**  
**LaRC**  
**JPL**

## CHAR's Toolbox

	CHAR	STAB	TD
Charring Ablation	X	X	
1D	X	X	X
2D	X		X
3D	X		X
Porous Flow	X		
Enclosure Radiation	X	X	X
Inverse	X		
Generalized mesh	X		
Contact conduction	X		X
Adaptive Mesh	X		
Thermal Stress	X		
Parallel	X		X
Rigorous Verification	X		
Fluid/Thermal Coupling	X		



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CHAR: New EA Ablation Tool!  
STAB: Legacy EA Ablation Tool!  
TD (Thermal Desktop/Sinda): EA Thermal Analysis Tool!



# Aerolab – High Performance Computing Facility



300 TB Lustre  
File System

**ICE  
8200**  
64x  
12-core  
Intel x5650™  
DDR IB  
2GB/Core

**ICE  
8200**  
64x  
12-core  
Intel x5650™  
DDR IB  
2GB/Core

**ICE  
8400**  
64x  
12-core  
Intel x5650™  
QDR IB  
4GB/Core

**ICE-X**  
48x  
16-core  
Intel E5-2670™  
FDR IB  
4GB/Core

500 TB  
Lustre  
File  
System